DURABILITY OF A HYBRID AIR-LAND VEHICLE

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ABSTRACT

A small hybrid vehicle has been developed and tested that is capable of flying, crawling, and transitioning between aerial and terrestrial locomotion modes. The Morphing Micro Air-Land Vehicle is a 16 inch wingspan craft proposed for advanced reconnaissance missions. Earlier versions of MMALV included several sources of low durability. Original prototypes relied on standard RC servos (modified for continuous rotation) as terrestrial locomotion drive motors. High impulse loads experienced during landing resulted in failure of these components, often after as few as two or three deployments. Battery containment was also an issue. During abrupt landings, the battery often became a destructive projectile within the fuselage. Another source of low durability was the method by which the motor was mounted to the fuselage. This was primarily an issue during the trimming process, during which crashes were sometimes unavoidable. Multiple improvements over the previous prototype are implemented that allow the vehicle to repeatedly survive the high impulse loading experienced during landing and even crashing. Compliance in each wheel-leg mitigates the peak level of the impulse load, and compliance in the terrestrial drive train limits the torque that is transmitted back to the drive motor. The custom-built drive train housing mates closely and is secured firmly to the fuselage. The housing also secures the battery. A motor nacelle designed into the fuselage allows for firm mounting of the motor, as well as reproducible placement and orientation of the motor. This both improved durability and decreased odds of crashing during trim flights. Improved wing designs were investigated to develop higher lift, thus allowing for lower cruising speed, which would reduce the loads experienced during landing.

1. INTRODUCTION

Military force commanders would be well served by a low-signature reconnaissance vehicle capable of being inserted into the battlespace at a moment's notice and lurking within a target area. One such vehicle would be a hybrid micro robot capable of the following mission sequence: 1) fly from a takeoff point to a target area (e.g. a building), 2) land stealthily within a target area (e.g. on a rooftop), 3) transform into a highly mobile land vehicle, 4) locomote successfully over ground obstacles (e.g. crawl to the edge of a roof or into a building), and 5) transmit critical data (visual, acoustic, chemical, etc.) from its position. Ideally, the vehicle would be able to take to the air from its recon position, and either move to another target or meet the deploying force en route. The Morphing Micro Air-Land Vehicle (MMALV) has been developed to fill this need in reconnaissance equipment.

1.1 Prior Development

The authors have previously designed, fabricated, and demonstrated a 12 inch wingspan vehicle (Fig. 1) that was capable of flying, landing, and crawling (Bachmann, et al., 2005). The vehicle also demonstrated the ability to regain flight by walking off the edge of a roof (Boria, et al., 2005). The 0.26 lb. vehicle had sufficient payload capacity to carry two miniature video cameras and an 80 mW, 2.4 GHz video transmitter.

Fig. 1. Early prototype hybrid vehicle.

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MMALV integrates the flexible airfoil developed at the University of Florida with the Whegs™ terrestrial robotic technology developed at Case Western Reserve University. The flexible airfoil is intended to improve the stability of the craft by rejecting atmospheric disturbances with passive adaptive washout (Ifju, et al., 2005). This behavior passively adjusts the airfoil's profile and apparent angle of attack to minimize disparity in lift produced between the two wings. The terrestrial drive technology has resulted in the fastest micro robot capable of surmounting obstacles on the order of the size of the robot (Morrey, et al., 2003).

1.2 Prototype Evaluation

Critical evaluation of the performance of the prototype vehicle identified several areas of necessary improvement. One critical requirement was for semi-autonomous operation. A military review panel concluded that it would be unreasonable to expect the warfighter to tele-operate MMALV. A COTS autopilot was identified to meet this need. Implementation of the autopilot is not presented in this paper, but the autopilot is of interest for this reason: while the selected autopilot is "small" and "lightweight" by industry standards, it still represents a significant increase (50 grams) in the total mass of the vehicle (118). This is important in light of the second critical weakness of the original prototype – lack of durability.

Fragility of the original prototype arose in three areas. The most prominent vulnerability was experienced within the terrestrial drive system. Several characteristics of the vehicle conspire to effect this weakness. The vehicle's small wing area requires a high cruise speed. As with any aircraft, the terrestrial running gear experience abrupt loading during the landing process. This is accentuated by the MMALV running gear – the shape of the wheel-legs makes them susceptible to snagging on features of the ground, including rocks, gravel, and grass. Furthermore, as the running gear is not free-spinning, but is actually driven, all of the resulting tangential loading is transmitted back to the drive motor. The end result of these circumstances is that even the most controlled landings strongly resemble a crash, from a dynamic loading standpoint. Testing of the early prototype demonstrated that the terrestrial drive motors could survive a very limited number of deployments.

A secondary source of limited durability was the mounting procedure for the propeller motor. On the early prototypes, a slot was hand-cut into the fuselage nose, and the motor was glued or epoxied into the slot, with only line contact on either side. The final source of fragility on the early prototype was the mounting mechanism for the battery. In an attempt to ensure the battery could be easily inserted and removed, insufficient mounting methods were utilized. Abrupt and crash landing frequently turned the battery into massive projectile with the fuselage, resulting in damage to the battery and other components.

Lack of durability represented multiple hurdles to the field deployment of MMALV. Operationally, low durability would result in short vehicle life-span. A military review panel agreed that, for MMALV to gain acceptance among warfighters in the field, the durability of the vehicle would need to be improved. In addition to adversely affecting the acceptance of MMALV by the military, low durability made it difficult to field each vehicle on an individual basis. The "hand-crafted" fabrication and assembly process results in variations between nominally identical vehicles. These variations require that each individual vehicle undergo several trim flights. During this process, R/C controller settings and vehicle control surfaces are adjusted to produce the desired flight characteristics, namely straight level flight when the elevator/rudder control input is zero. Variations between distinct vehicles sometimes cause crashes during these trim flights. Due to low durability, these crashes often resulted in component failure or component separation from the vehicle.

1.3 Scope

This paper describes the improvements implemented on the original prototype that allow the new model to repeatedly survive the high impulse loading experienced during landing. Two improvements to the terrestrial drive system are described, along with two improvements to the fuselage design. Results of wing aerodynamic studies are also presented.

2. TERRESTRIAL DRIVE SYSTEM

2.1 Power Delivery

Figure 2 shows an assembled view of the final design of the terrestrial drive system. Each wheel-leg is powered by a Solarbotics™ GM13a gearmotor (1), which produces 14.9 in-oz of torque at start-up, and 113 rpm under no load. A 26-tooth 48-diametral-pitch gear (2) mounted to the motor output shaft adaptor (3) impels a 36 tooth gear (4) that is press fit onto the outer cylinder (5) of the friction clutch mechanism. Figure 3 shows an exploded view of the entire unit. The clamshell design of the friction clutch outer cylinder eases assembly of the unit, and the internal shoulder controls the lateral position of the outer cylinder. Three 5/16" I.D. x 1/2" O.D. quad-profile o-rings (6) transmit power from the outer cylinder to the inner cylinder (7a, 7b). The O.D. of the inner cylinder is sized to produce a breakaway torque of approximately 24.7 in-oz. Transmitted through the 26:36

gear reducer, the back-torque applied to the motor is limited to about 120% of the motor's stall torque. The two-piece inner cylinder has internal flats that positively engage the wheel-leg axle (8). The snap ring (9) at the end of the inner cylinder fits into the groove on the wheel-leg axle, allowing for quick insertion and removal of the wheel-leg axle.

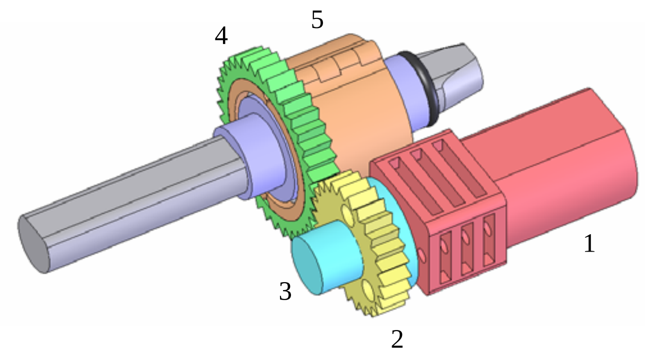

Fig. 2. The new terrestrial drive system power plant

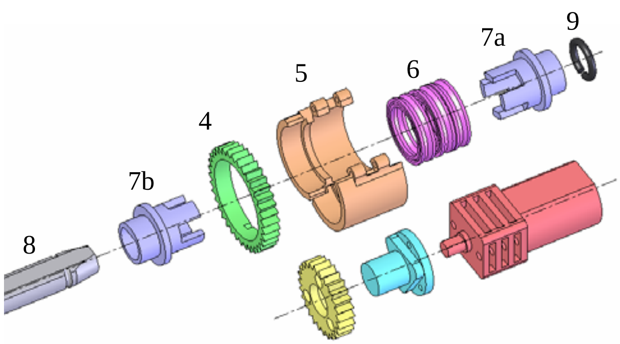

Fig. 3. Exploded view of the terrestrial drive system

The drive system depicted in Figures 2 and 3 resulted from multiple iterations of the design/build/test process. While the RC servos implemented on the original prototype were a significant source of failure, this was still an attractive option due to the simplicity of the implementation. For initial models of the larger craft, stronger servos were selected. The BMS 380-Max servo was selected because it offers metal gears and more power than other servos of similar size. Flight tests with this implementation quickly illuminated multiple failure modes. One common failure mode centered on the potentiometer output shaft. This 0.052 inch diameter shaft serves as the mounting shaft for several of the servo transmission gears, including the output gear/shaft combo. While the output gear/shaft is supported by a bearing where it exits that servo body, sufficient radial load on the output horn could result in bending of the potentiometer shaft, rendering the servo transmission useless. Another failure mode was a result of the injection molded plastic servo body. At the top of the servo, the body acts as the bearing housing for the output gear/shaft bearing. Multiple energetic landings were found to fatigue, crack, and eventually separate the bearing housing from the remainder of the servo body.

2.2 Wheel-leg Design

The final wheel-leg design is shown in Figure 4. The 0.25 inch wheel-leg axle has six longitudinal grooves milled into the distal end. The wheel-leg spokes are shaped from 0.062 inch diameter steel music wire. One-inch long tabs on the wheel-leg spokes mate to the grooves on the wheel-leg axle. The spokes are attached to the axle using Kevlar thread, a screw, and a washer. The Kevlar thread holds the spoke tabs firmly against the axle, but do not prohibit them from rotating or sliding out along the axle. The screw and washer prevent the spokes from sliding out from under the threads and dampen the rotational movement of the spokes. The combined result is a small amount of torsional compliance in the wheel-leg spokes, as shown in Figure 5.

Fig. 4. The final wheel-leg design, including axle

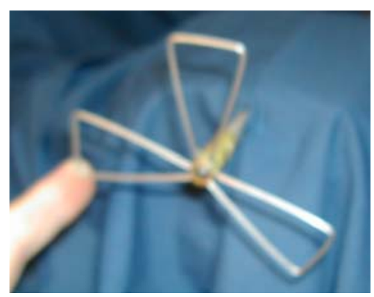

Fig. 5. The final wheel-leg design, including axle

3. FUSELAGE DESIGN

Two significant improvements were made in the fuselage design to increase the durability of the current model. A motor nacelle provides a strong, reproducible mounting surface for the propeller motor, and the terrestrial drive system housing represents a significant improvement over the injection molded plastic housing inherent to the RC servo drive motor.

3.1 Fuselage Insertion

Figure 6 and Figure 7 show assembled and exploded views, respectively, of the housing for a left-side wheel-leg drive system. The outer layer (1) of the housing is shaped to mate perfectly to the inner surface of the fuselage. This layer also holds bearings for the motor output shaft adapter (hole A) and the wheel-leg drive system axle (hole B). The middle layer (2) holds the output end of the drive motor, the output shaft of which passes through C. The inner layer (3) closes around the drive motor transmission (D), and holds the bearing (hole E) that supports the inner end of the wheel-leg drive axle.

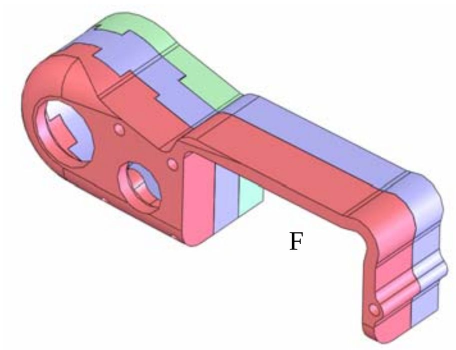

Fig. 6. Terrestrial drive system housing

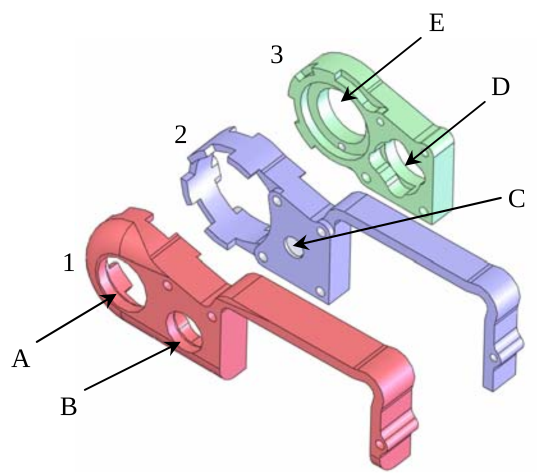

Fig. 7. Exploded view of terrestrial drive system housing

The sandwiching effect of the middle and inner layers serves to hold the motor in place without mounting screws, and also protect the motor transmission from debris. Earlier implementations using the Solarbotics™ gearmotor showed that the miniature gears in the exposed gearmotor were susceptible to becoming clogged by dirt and sand particles that entered the fuselage during landing. Pockets F on opposite sides of the fuselage serve to successfully secure the battery in place, while also allowing for rapid loading of the battery through the side of the fuselage.

3.2 Motor Nacelle

To allow for more durable attachment of the motor to the fuselage, a prominent motor nacelle was designed into the fuselage (Figs. 8 and 9). Design of the motor nacelle was complicated by the operational specifications of MMALV. It was critical that the motor propeller survive the landing experience, so that the vehicle could regain flight after performing its surveillance duties. For this reason, it was desirous to elevate the nacelle to the maximum extent possible on the fuselage. However, placing the propeller directly in front of a large blunt nose would impair the thrust generation of the propeller, and adversely affect the efficiency of the craft. Simultaneously, the nose is also an advantageous location to mount a micro-camera, to survey the area directly in front of and below the vehicle. This design survived a high speed, head-on collision with the ground.

Fig. 8. Close-up of the fuselage nose

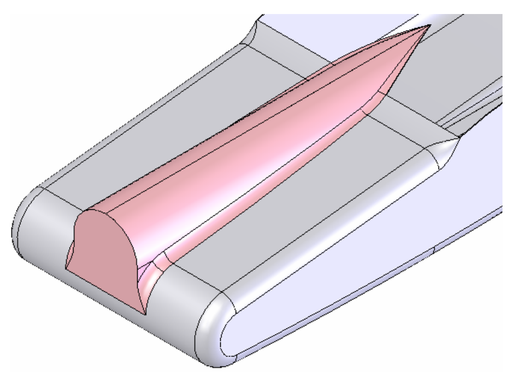

Fig. 9. Rendering of the motor nacelle

4. PERFORMANCE IMPROVEMENTS

A final consideration for reducing the impulse loads experienced during landing was to reduce the cruising speed of the vehicle by increasing the lift generated by the wing. To this end, a series of wings were testing in a wind tunnel, using standard apparatus for measuring the lift, drag, and moment produced by the airflow over the wing. Five wing parameters were varied over the ten wings: 1) airfoils shape, 2) planform shape, 3) airfoil

flexibility, 4) winglets, and 5) curvature of the leading edge. Two airfoil shapes were investigated: a) the custom profile (UF) implemented on the original prototype, which included recurve, and b) the mean chord line of the NACA 8300 airfoil. Three planform shapes were investigated: a) rectangular, b) elliptical, and c) tapered. Most of the wings were fabricated using the flexible fabric, while two were constructed out of solid carbon fiber. Wings were constructed with and without winglets. Finally, the curvature of the leading edge was investigated – the carbon fiber fabrication process typically resulted in a thin, knife-like leading edge. For two of the wings, the leading edge was built-up with a 1/8 inch diameter rod, to produce a more definite curvature to the leading edge. Table 1 summarizes the various wing parameter combinations that were tested. Wing 9 represents the 16 inch wingspan version of the wing used on the original prototype.

Table 1. Summary Descriptions of Wings Tested

Wing #	**Airfoil**	**Plan-form**	**Flex**	**Wing-lets**	**Lead edge**
0	8300	Rect	Flex	No	No
1	UF	Rect	Flex	No	No
2	UF	Rect	Rigid	No	No
3	8300	Rect	Rigid	No	No
4	8300	Ellipse	Flex	Yes	No
5	UF	Ellipse	Flex	Yes	No
6	UF	Tapered	Flex	No	Yes
7	8300	Rect	Flex	No	Yes
8	8300	Ellipse	Flex	No	No
9	UF	Ellipse	Flex	No	No

Table 2 summarizes the results of wind tunnel testing performed on the several wings enumerated in Table 1. As can be seen from the data, all of the wings outperformed the original wing in terms of C_L and L/D. Wings 4 and 5 produced some the the highest coefficients of lift, demonstrating the winglets provide improved lift even at the scale and aspect ratio range encountered here. Unfortunately, pilot evaluation of Wing 4 concluded that the controllability of the aircraft was compromised due to the winglets. The likely reason for this is that it was necessary to reinforce the wingtips to support the winglets. This may have resulted in decreased flexibility in the wing fabric, thus limiting the passive adaptive washout that could occur. The 8300 airfoil with elliptical planform, flexibility, and no winglets provide the next best combination of max C_L and max L/D.

Table 2. Summary Airfoil Analysis Data

Wing #	**Max C_L**	**α at Max C_L**	**Max L/D**	**α at Max L/D**
0	1.5	16.3°	11.5	5.5°
1	1.3	17.3°	10.9	7.9°
2	1.3	17.9°	9.9	7.8°
3	1.6	16.2°	10.3	4.5°
4	1.7	14.3°	11.9	7.5°
5	1.5	18.0°	11.4	8.8°
6	1.3	15.9°	10.9	8.5°
7	1.5	14.6°	10.2	4.7°
8	1.5	16.3°	12.5	4.8°
9	1.2	16.8°	9.5	5.2°

CONCLUSIONS

The improvements presented here demonstrate that it is feasible to develop a multi-mode capable vehicle for reconnaissance missions. The current MMALV model (Fig. 10) enjoys sufficient durability to be deployed multiple times. Compliance in the drive system mitigates the strength of the impulse loading experienced during landing. Improved mounting methods for the propeller motor, terrestrial drive system, and battery allow the vehicle to successfully withstand the remaining impulse loads of multiple crashes and landing. The authors believe that future developments will result in a field-ready vehicle capable of extended surveillance missions. In the near future, MMALV will be available as a reconnaissance tool for force commanders at every level, allowing for rapid deployment, stealthy insertion into the target zone, and persistent presence within that zone.

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Fig. 10. The current MMALV model

REFERENCES

Bachmann, R.J., F.J. Boria, R.D. Quinn, J.E. Kline, R. Vaidyanathan (2005), "Utility of a Sensor Platform Capable of Aerial and Terrestrial Locomotion," IEEE Conf. on Advanced Intelligent Mechatronics.

Boria, F.J., R.J. Bachmann, P.G. Ifju, R.D. Quinn, R. Vaidyanathan, C. Perry, J. Wagener (2005), "A sensor platform capable of aerial and terrestrial locomotion," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS05).

Ifju, P.G., S. Ettinger, D.A. Jenkins, and L. Martinez (2001), "Composite Materials for Micro Air Vehicles," SAMPE Journal, **37**(4).

Morrey, J.M., B. Lambrecht, A.D. Horchler, R.E. Ritzmann, R.D. Quinn (2003), "Highly Mobile and Robust Small Quadruped Robots", IEEE International Conference on Intelligent Robots and Systems.